5. 2D Model and Results

Initial Temperature Conditions

The initial temperature conditions and model geometry used in the two-dimensional thermal analyses were extrapolated from existing instrumentation and borehole information, as well as the historical background of tailings deposition in the West Twin Disposal Area. Effectively, a worse-case, "composite" scenario was developed for the analysis. A composite cross-section was created using the deepest possible tailings deposits and the greatest possible talik extent within the tailings. The main components of the two dimensional model are displayed on Figure IX-3.

Figure IX-4 illustrates the approximate locations of the geothermal instrumentation used in the development of the initial temperature profile. Temperature profiles recorded in these instruments are also indicated in this figure as numbers located at the corresponding depths beside the instrument. The instruments chosen for this profile were those that represented the most conservative values, such as the deepest extent of thawed tailings or the warmest temperatures. Thermocouple 03-04, located approximately 150 m from the south abutment of the WT Dike, was used as a basis for the thermal profile outside of the influence of the tailings talik.

The initial thermal regime, as used in the base case analysis, can be seen in Figure IX-5. This figure also contains the location of the thermal instrumentation and the interpreted thawed zones used for establishing the initial thermal regime.

All of the bedrock located below the area that was once submerged by the former West Twin Lake is represented in the base case analysis as being part of the Surface Cell talik, as shown on Figure IX-5. This was considered the most conservative estimate for an area where there is no existing thermal data.

It was also assumed that if the bottom nodes of a thermistor or thermocouple indicated thawed tailings, then the thawed zone continued down to the tailings/bedrock contact. This is also illustrated in Figure IX-5. This was considered the most conservative estimate of the depth of the Surface Cell tailings talik in areas where limited data was available at depth.

A conservative initial temperature profile in the upper 2 m of the model was used, as can be seen in Figure IX-5. The thermal profile used, which consisted of 5°C at the surface to 1°C at a depth of 2 m, was based on seasonal climate values for the start date and conservative estimates of tailings temperatures. A nominal start date of July 1 allowed for the most gradual impact from outside air temperatures and made for a smoother start for the long-term thermal modelling.

A warm deposit of tailings can be seen in Figure IX-5 on the surface of the Surface Cell between the horizontal distance of 390 and 420 m. The location of this warm deposit coincides with the location of the pond that still exists, as of 2003, on the Surface Cell. This deposit was given warmer initial temperatures than surrounding tailings since it is assumed that tailings deposited at this location will be approximately similar to air temperatures as of the model start date, July 1. The thermal profile within this area is 8°C at the surface cooling to 1°C at a depth of 4 m.

Boundary Conditions

Once the climatic and material properties of the thermal model have been established, the boundary conditions can be applied. Boundary conditions may be specified as temperature, total flux or flux per unit length along the side of an element. The following is a description of the boundary conditions as used in the two dimensional analysis.

Ground Surface Temperature

The ground surface temperatures used in the model were developed within the TEMP/W software. TEMP/W utilizes the above mentioned climatic data to calculate an effective ground surface temperature. The effective temperature is calculated considering the effects of the snow cover on the surface albedo, convective heat loss due to wind and the net effects of the weather data on the long-wave and short-wave solar radiation infiltration. This effective ground surface temperature can then be applied as a boundary condition on the surface of the model.

These effective ground surface temperatures were applied to all ground surfaces within the model except the crest and sideslopes of the West Twin Dike. On these areas, it was assumed that no snow would accumulate due to wind effects and based on site observations. For these surficial areas, a temperature function was developed in the same manner as the effective ground surface temperature methodology mentioned previously. However, in order to account for the lack of snow, the climatic input for precipitation was reduced to zero over the course of the year. As a result, the effective ground surface temperatures for the crest and the downstream slope were colder than the overall effective ground surface temperatures applied to the remainder of the surface.

A plot of the TEMP/W calculated annual total accumulated snow cover can be found in Figure IX-6. The accumulated snow depth values as calculated in TEMP/W are determined by an automated function based on daily values for temperature, wind speed and precipitation. Also in Figure IX-6 is the mean snow depth values as calculated at the Resolute Airport AES Station. The Resolute weather station was chosen since snow depths have been recorded at this location since 1955, whereas snow depth data is only available at the Nanisivik weather station since 1981. The Nanisivik data also contains insufficient data to develop appropriate monthly average values.

Lateral Permafrost Temperatures

Since the lateral permafrost at depth, beyond the historical warming from the tailings deposition, would act as a heat sink to the Surface Cell talik, it was represented as a boundary condition in the model. The boundary condition at this location is represented by a fixed temperature profile, which is extrapolated from existing thermal instrumentation and thermal properties of the bedrock. This boundary condition is illustrated in the lateral extent of the model in Figure IX-3 and is only applied to the left side of the model, since it is within the regional permafrost. The right side of the model does not have an applied fixed temperature profile since it is under the area of the former West Twin Lake and is therefore still assumed to be apart of the talik. It is effectively assumed that there is no heat flow through this right side of the model.

Geothermal Flux

The geothermal flux boundary, as applied to the base of the 2-dimensional model, was noted previously.

Freezeback Analysis

The following is a description of the freezeback analysis for the base case scenario (mean annual air temperatures and no shale cover), which is defined by the boundary conditions mentioned above.

Areas of interest with respect to the thermal modelling results include the following three points:

1. the depth of freezing after 7 years,
2. when the tailings are frozen below the 371 m elevation mark, and
3. when the entire tailings deposit becomes frozen.

The 371 m elevation is used as an important benchmark for depth of freezing since it is the approximate elevation of the bottom of the West Twin Dike. The total depth of the tailings within the thermal model is approximately 33 m at the deepest point (353 m elevation).

Figure IX-7 shows a time lapse of the results from the base case thermal model. Contours of approximately every five years are included, as well as year 7 and the time intervals where the freeze/thaw line is at elevation 371 m and 353 m. The freeze/thaw line is always represented as the -0.2°C contour line.

After 7 years, the tailings freeze 14 m down to an elevation of 371.8 m. The time required for the tailings to freeze 15 m to the 371 m elevation mark is approximately 7.4 years. The time required for the tailings to freeze 33 m to the bedrock at 353 m elevation is approximately 27 years.

The time to freezeback of the talik edge under the WT Dike is of interest for the purposes of stability analyses of the shale dike. The talik edge under the WT Dike is defined as the tailings at a horizontal distance greater than 551 m in the model and above an elevation of 369.6 m. Figure IX-8 illustrates the area of interest under the shale dike, initial temperature freeze front location and the location of the freeze front at the time it reaches the edge of the envelope. The time required for complete freezeback below the envelope of the shale dike is 4.9 years.

Parametric Analyses

In addition to the base case analysis discussed above, a number of parametric analyses were conducted to determine the effects of varying conditions on the model. These analyses included accounting for the following variations:

- Increasing the temperature of the talik below the bottom depth of the tailings;
- The addition of a shale cover over the tailings;
- The addition of global warming to the climate data; and
- The addition of global warming over 50 and 100 years after freezeback of the tailings occurs.

The above mentioned analyses were compared against the base case scenario discussed previously. As a basis of comparison, the freezeback rate was compared after 7 years and comparisons were also made for time to freeze to the 371 m and 353 m elevations. As mentioned earlier, 371 m elevation is equivalent to the base elevation of the dike and 353 m elevation is equivalent to the deepest depth of the tailings. A summary of the varying results of the parametric analyses can be found in Table IX-4.

Mean Annual Air Temperatures, No Shale Cover, Warmer Original Talik Temperatures

The base case analysis assumes that any bedrock that was below the former West Twin Lake is thawed. It also assumes that all talik temperatures are 0.1°C, as recorded in thermal instrumentation within the tailings on-site. None of the thermal instrumentation penetrates the bedrock to a significant depth and little is known about the thermal regime within the bedrock below the tailings.

A parametric analyses was set up to determine the effects of a warmer talik below the tailings than that assumed in the base case scenario. All boundary conditions remained the same as in the base case scenario, however, the initial temperature conditions were changed. The talik temperatures inside of the tailings remained the same; only the bedrock talik temperatures were increased.

To define the initial temperature conditions in the model, the talik thermal regime below the tailings was determined using the steady state heat flow under an infinite strip technique as described in Andersland and Ladanyi (1994). A 2-dimensional plot of the temperature regime as calculated using this technique can be found in Figure IX-9. Figure IX-10 shows the thermal contours as used in the parametric analyses. The base case initial temperature thermal contours can be seen in Figure IX-4.

Figure IX-11 shows a time lapse of the results from the base case with warmer talik thermal model. Contours of approximately every five years are included in Figure IX-11 as well as the year 7 contour and the time intervals where the freeze/thaw line is at elevation 371 m and 353 m.

After 7 years, the base case and the warmer talik case were both frozen to a depth of 13.8 m. Both analyses also reached the 371 m elevation at the same time period of approximately 7.4 years. The warmer talik model took 3 years longer to freeze to the bottom of the tailings at a depth of 33 m below the surface. A warmer talik below the tailings scenario has limited effects on the freezeback rate of the talik in the upper 15 m, but results in reduced rates at depth as the phase change boundary approaches the warmer bedrock.

Mean Annual Air Temperatures, with Shale Cover

A shale cover was added to the base case scenario in order to determine the effects that it would have on the permafrost aggradation rates. All of the boundary conditions are the same for the shale cover model as they are in the base case scenario. The only difference between the two models is that a 1.2 m shale cover was placed above the tailings.

Figure IX-12 shows a time lapse of the results from the shale cover thermal model. Contours of approximately every five years are included in Figure IX-12 as well as the year 7 contour and the time intervals where the freeze/thaw line is at elevation 371 m and 353 m.

After 7 years, the shale cover analyses was frozen to a depth of 13.2 m (372.4 m elevation), compared to the 13.8 m depth in the base case scenario at the same time. The time required to reach the 371 m elevation was approximately 7.4 years in the base case and 8.1 years in the shale cover analysis. The time required to reach the 353 m elevation was approximately 27.1 years in the base case and 28.1 years in the shale cover analysis. The effects of placing a shale cover on the tailings had minor effects on the overall time periods for freezeback of the tailings. Effectively, the additional time required to freeze the tailings is a result of the time required to freeze an additional 1.2 m of shale.

Global Warming Scenario, With Shale Cover

The climatic data that was used in the base case models was mean annual weather conditions derived from historical data. Since a more conservative approach would consider the effects of global warming, a global warming analysis was conducted to determine potential effects. In order to consider the potential effects of global warming on the freezeback times of the tailings, global warming functions were added to the boundary conditions. A conservative climate warming amount of greater than 5°C over 100 years was added to the mean annual air temperatures. The global warming analysis was compared to the shale cover analysis mentioned above.

The daily changes to the boundary conditions were so subtle that a one dimensional model was used rather than a two-dimensional model. A one dimensional model could be run with more stringent tolerances to better analyse the effects of the global warming and still be completed within a reasonable time frame. A 1-D climate warming model was compared to a 1-D model without warming. At the conclusion of the two models, a percent difference in the time required for freezeback was developed and translated into the results from the 2-D models.

Based on the 1-D model of global warming, the additional time required to freeze the tailings under a shale cover to the 371 m elevation was 1.4%. This would be equivalent to an additional time period of 41 days to reach the 371 m elevation in the 2-D analyses. The total time to reach 371 m would be approximately 8.2 years, compared to 8.1 years without global warming.

The additional time required to freeze the tailings under a shale cover to the 353 m elevation was 9.4%. This would be equivalent to an additional time period of 2.6 years to reach the 353 m elevation in the 2-D analyses. The total time to reach 353 m would be approximately 30.7 years, compared to 28.1 years without climate warming.

The addition of global warming to the climatic data had little effect on the freezeback rates early in the thermal model but had greater impacts over longer time periods.

Shale Cover, Mean Annual Air Temperatures until All Tailings Frozen, then 50 and 100 Years of Global Warming

A further analysis was conducted to determine the effects of climate warming in the long term. The shale cover analysis was used as a basis for this analysis. The shale cover model was run using historical mean annual climate data until the tailings were completely frozen. Then the model was allowed to continue for another 100 years adding warming functions to all of the boundary conditions. The purpose of this analysis was to determine if long term global warming changes would lead to an eventual re-thawing of the tailings deposits.

The shale cover model was allowed to run until the tailings were completely frozen, which was 28.1 years. At this point, the boundary conditions were altered to accommodate global warming changes. A warming trend of greater than 5°C was added over 100 years, as discussed above.

Changes were made to the following boundary conditions, ground surface temperatures and lateral permafrost conditions. The ground surface conditions were altered to include the annual air temperature warming. The lateral permafrost conditions were also changed to account for the eventual changes to the permafrost regime over time as a result of global warming. A 1-D model was established to determine the change in the local permafrost regime in order to determine the lateral permafrost boundary condition.

Figure IX-13 shows the initial temperature conditions profile of the Surface Cell prior to the application of global warming to the boundary conditions. After freezeback and an additional 50 years of global warming, the freeze front was below the lower limits of the model and the body of the tailings was continuing to get colder. Figure IX-14 shows the thermal regime of the tailings after freezeback and an additional 50 years of climate warming. With 100 years of global warming after freezeback, the freeze front was still below the lower limits of the boundary and the tailings were still continuing to get colder. Figure IX-15 shows the thermal regime of the tailings after freezeback and an additional 100 years of global warming.

The thermal modelling does not indicate that climate warming causes the tailings to warm up in the period 100 years after freezeback.

6. Conditions Not Accounted For

There are several limitations to the modelling results discussed in this appendix. Some of the conditions that were not be accounted for included the following:

1. Solute cryoconcentration with significant freezing point depression.
2. Convective heat transport by groundwater flow.
3. Three-dimensional effects resulting from end effects on the talik.

As noted in numerous research papers, convective heat transport with associated freezing point depressions between drained lakes is responsible for the accelerated rate of permafrost aggradations in these features.

Table IX-1: Average Daily Climatic Values

Month	Temperature (°C) Maximum	Temperature (°C) Minimum	Relative Humidity (%) Maximum	Relative Humidity (%) Minimum	Wind Speed (m/s)	Precipitation (mm)
January	-26.5	-32.1	75.4	75.4	6.42	0.24
February	-27.3	-33.1	61.7	61.7	6.42	0.14
March	-24.7	-30.8	74.8	74.8	6.1	0.24
April	-16.6	-23.4	74.4	74.4	6.1	0.33
May	-7.8	-13.5	84.1	84.1	6.42	0.56
June	1.9	-2.8	85.3	85.3	6.42	0.0
July	7.4	2.5	80.8	80.8	6.1	1.14
August	3.7	-0.8	88.5	88.5	6.42	1.32
September	-3.8	-7.6	91.8	91.8	7.3	1.45
October	-12.6	-17.2	88.2	88.2	7.03	1.0
November	-19.9	-25.4	79.8	79.8	6.72	0.53
December	-22.0	-29.4	74.9	74.9	6.42	0.24

Table IX-2: Summary of Soil / Rock Parameters

Unit Description	Thermal Conductivity (W/m°C) Thawed	Thermal Conductivity (W/m°C) Frozen	A	B	Volumetric Water Content (%)	Volumetric Heat Capacity (kJ/(m³ °C)) Frozen	Volumetric Heat Capacity (kJ/(m³ °C)) Unfrozen	Dry Density (Mg/m³)
Shale Cover	2.46	2.89	0.05	-0.4	34.6	2716	3991	1.8
Tailings	1.9*	3.2*	0.04	-0.2	37.8*	4100	6224	2.5
Shale Bedrock	1.72	1.98	0.05	-0.3	12	2772	3443	2.7

*Based on EBA lab results, 2003.

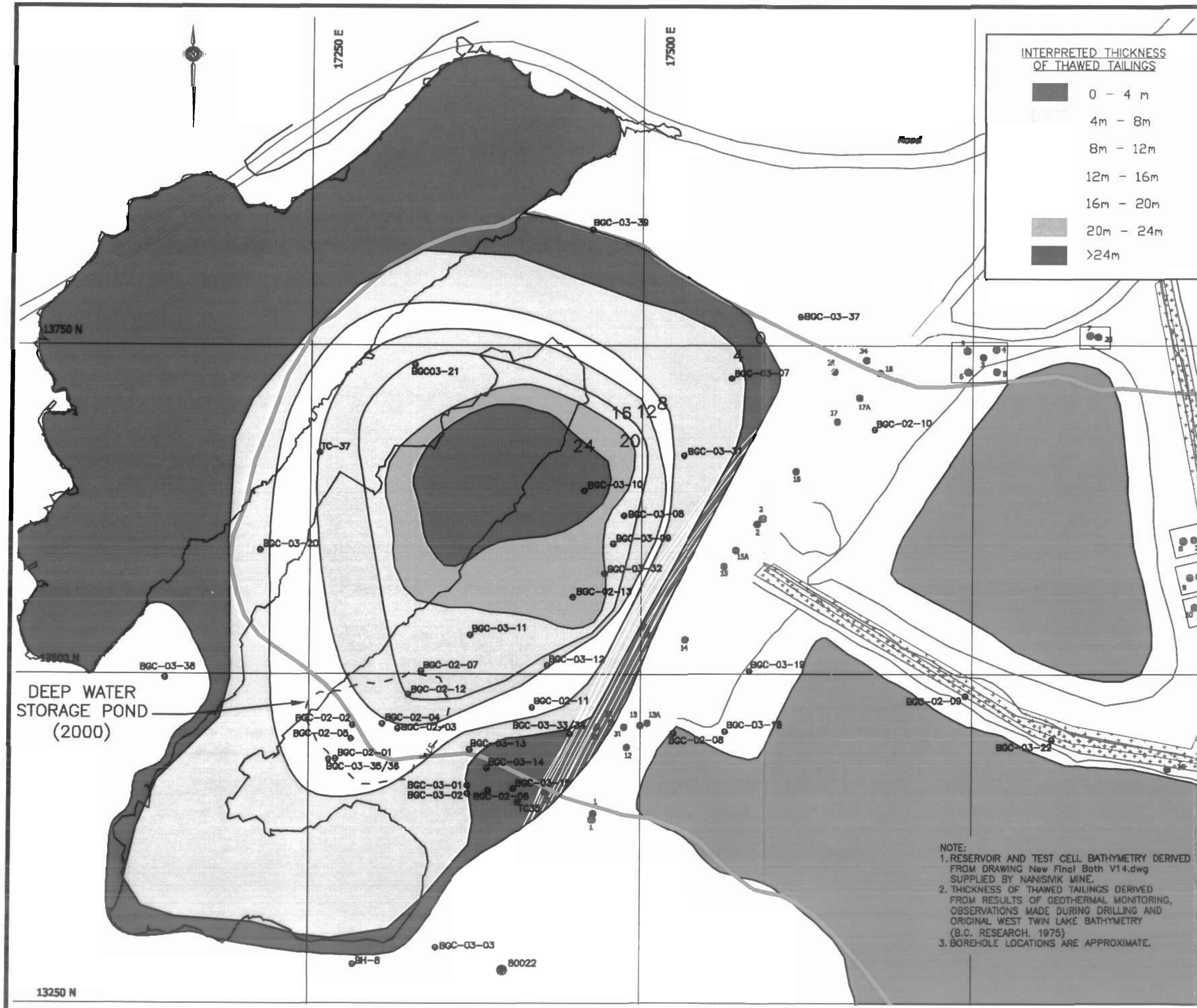
Table IX-3: 1D Model Calibration - Daily Climatic Values Comparison

	Mean Monthly Air Temperature (°C) (1976-2003)		Mean Monthly Air Temperature (°C) (2002 – 2003)		Month-End Snow Depths (cm)	
Month	Maximum	Minimum	Maximum	Minimum	Model	Actual
Oct 2002	-12.6	-17.2	-9.3	-11.5	6	8
Nov 2002	-19.9	-25.4	-18.9	-21.4	10	14
Dec 2002	-22.0	-29.4	-20.9	-23.2	11	20
Jan 2003	-26.5	-32.1	-21.1	-24.1	13	27
Feb 2003	-27.3	-33.1	-28.2	-30.5	14	27
Mar 2003	-24.7	-30.8	-20.4	-23.6	15	19
Apr 2003	-16.6	-23.4	-18.4	-20.9	17	16
May 2003	-7.8	-13.5	-6.6	-8.6	19	15
Jun 2003	1.9	-2.8	2.0	0.0	21	1
Jul 2003	7.4	2.5	9.6	6.3	0	0
Aug 2003	3.7	-0.8	2.1	.3	1	0
Sep 2003	-3.8	-7.6	-3.7	-5.1	10	3
Oct 2003	-12.6	-17.2	N/A	N/A	17	N/A
Nov 2003	-19.9	-25.4	N/A	N/A	20	N/A

Table IX-4: Summary of Parametric Analyses

		Time at 371 m		Time at 353 m	
Case	Depth after 7 Years	Days	Years	Days	Years
MAAT, No Cover (Base Case)	371.8 m	2700	7.4	9900	27.1
MAAT, No Cover, Warmer Talik at Depth	371.8 m	2700	7.4	11070	30.3
MAAT, Shale Cover Added	372.4 m	2970	8.1	10260	28.1
Global Warming, Shale Cover		3012	8.2	11224	30.7
Shale Cover, 50 years of G.W. after MAAT Freezeback of Tailings	Freeze front below 330 m after 50 years, and still dropping				
Shale Cover, 100 years of G.W. after MAAT Freezeback of Tailings	Freeze front below 330 m after 100 years, and still dropping				

0255-008-03 007 FIGURE_IX-1.dwg



CLIENT: NANISIVIK MINE
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LEGEND

- 2002/2003 GEOTECHNICAL BOREHOLE/TEST PIT
- ORIGINAL LAKE OUTLINE (APPROXIMATE)
- CURRENT AREA OF PONDED WATER IN SURFACE CELL (SEPTEMBER 2003)
- SYMBOL DENOTES THERMOCOUPLE LOCATION
- SYMBOL DENOTES FROST GAUGE LOCATION

60m 0 60m 120m 160m

REV.	DATE	REVISION NOTES	DRAWN	CHECKED	APPROVED

SCALE:	AS SHOWN
DATE:	JAN 2004
DRAWN:	CJT
DESIGNED:	GKC
CHECKED:	JWC
APPROVED:	JWC

PROJECT: ASSESSMENT OF SURFACE CELL AND TEST CELL TALIKS

TITLE: TALIK MAGNITUDE AND EXTENT

PROJECT No.	DWG No.	REV.
0255-008-03	IX-1	0

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